Renewable and Sustainable Energy Reviews 33 (2014) 110–116

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Solar dryers with PCM as energy storage medium: A review

S.M. Shalaby [a,*], M.A. Bek [a], A.A. El-Sebaii [b]

[a] Department of Engineering Physics and Mathematics, Faculty of Engineering, Tanta University, Tanta, Egypt
[b] Department of Physics, Faculty of Science, Tanta University, Tanta, Egypt

ARTICLE INFO

Article history:
Received 8 June 2013
Accepted 31 January 2014
Available online 22 February 2014

Keywords:
Solar drying
Storage material
PCM

ABSTRACT

Using phase change material (PCM) as an energy storage medium is one of the most efficient ways of storing thermal energy. The latent heat storage provides much higher storage density than sensible heat storage, with a smaller temperature difference between storing and releasing heat. In addition, phase change materials provide constant and moderate temperature which is needed for drying most agriculture crops sufficiently. This paper reviews the previous work on solar drying systems which implemented the phase change material as an energy storage medium. It is concluded that the solar dryer with a PCM reduces the heat losses and improves the efficiency of the system. Furthermore, this review paper summarizes the previous methods that have been used for improving the thermal conductivity of the used phase change material particularly paraffin wax since it is commonly used as a storage medium in solar drying systems. It is inferred that carbon fibers, expanded graphite, graphite foam and high thermal conductive particles may improve the thermal efficiency of solar energy devices employing paraffin waxes as thermal energy storage media.

© 2014 Elsevier Ltd. All rights reserved.

Contents

1. Introduction

One of the potential applications of solar energy is the supply of hot air for drying agricultural crops and heating buildings during winter [1]. Solar dryers are classified as direct solar dryers, indirect solar dryers, mixed mode and hybrid solar dryers. Solar drying systems are also categorized into two general groups: natural and forced convection solar dryers. In direct mode solar dryers the drying material is heated directly by the solar radiation and the hot air is present in the dryer enclosure. The indirect solar dryer essentially consists of a solar air heater, a drying chamber and a blower to duct the heated air into the drying chamber. In the mixed-mode solar dryer the material to be dried is heated by both the solar radiation and the warm air coming from the solar air heater.

Due to the intermittent nature of solar energy, energy storage materials are used to store excess energy during the peak time of

* Corresponding author.
E-mail address: saleh_shalaby@yahoo.com (S.M. Shalaby).

http://dx.doi.org/10.1016/j.rser.2014.01.073
1364-0321 © 2014 Elsevier Ltd. All rights reserved.

solar radiation to be used in off-sun hours or when the energy availability is inadequate. The storage materials improve the energy systems by smoothing the output and thus increasing reliability. Thermal energy can be stored as sensible heat, latent heat and chemical energy. In sensible heat storage, thermal energy is stored during the rise of temperatures of the thermal storage material. The solid-state thermal storage materials, including sand, gravel, limestone, concrete and fire bricks, are commonly used as sensible heat storage materials. Bal et al. [2] tabulated in their review the solid and liquid materials used as sensible heat storage media for drying agricultural food products. The effect of using gravel, limestone and iron scrapes as sensible heat storage on the thermal performance of the double pass solar air heater was theoretically and experimentally studied by El-Sebaii et al. [3]. They concluded that the thermo-hydraulic efficiency of the heater with gravel is found to be higher than that without storage by 22–27%. An indirect type natural convection solar dryer with sand as sensible heat storage was investigated experimentally by El-Sebaii et al. [4]. They concluded that the final moisture content M_f for seedless grapes is reached after 60 and 72 h when the system is used with and without sand as the sensible heat storage material, respectively. The common advantage of using sensible heat storage is its low cost compared to the high cost of latent heat storage; however, the stored heat cannot be delivered at a nearly constant temperature which reduces the efficiency of the storage systems.

Latent heat storage systems using phase change materials (PCMs) provide a high energy storage density and have the ability to store energy at a constant temperature. For example, it takes eighty times as much energy to melt a given mass of water (ice) than to raise the same amount of water by 1 °C [5]. Thermo-physical properties of the PCM at the melting temperature are important in determining the material's suitability [6]. There are some essential physical properties of the PCM that should be identified in order for it to be used. These properties include the following: high specific heat and heat of fusion; high density and thermal conductivity; stable composition; chemically inert; and non-toxic. On the other hand, there are several factors which limit the use of PCM such as it being a novel technology, with limited space availability, high initial cost and irregular sunshine [7].

2. Review of solar dryers with PCM as energy storage medium

There is limited information regarding the use of latent heat storage to conserve thermal energy during drying. Devahastin et al. [8] investigated numerically the use of latent heat storage to store energy from the exhausted gas of a modified spouted bed grain dryer. Devahastin and Pitaksuriyarat [9] studied the effect of using paraffin wax as the thermal energy storage medium for drying kinetics of food products. Their proposed system consists of a compressor, a temperature controller, a heater and a latent heat storage (LHS) vessel. The used vessel is a cylindrical acrylic vessel with a diameter and a height of 0.10 and 0.20 m, respectively. The heated air from the solar heater flows through the LHS vessel in a copper tube with a diameter of 1.27×10^{-2} m attached with 18 fins which have the diameter of 0.08 m, thickness of 5.0×10^{-3} m and spacing between two adjacent fins of 0.01 m. They studied the temperature profiles at different positions. The authors of Ref. [9] used a non-insulated vessel to visually monitoring the melting/freezing processes. In addition, the effect of insulation on melting/freezing processes was also studied. The proposed LHS system could save energy during drying of a sweet potato by approximately 40% and 34% when using inlet air velocity of 1 and 2 (m/s), respectively.

Bal et al. [10] designed and developed a solar dryer which uses paraffin wax as a PCM to store excess solar energy during the daytime. They use hot air at temperatures close to those exhausted from a typical solar collector and release it when no solar energy is available. This implies the possibility of reducing the amount of energy required in the drying operation. In addition, they highlighted the possibility of drying agricultural/food products at steady and moderate temperatures of 40–75 °C.

A novel type of a solar dryer to evaluate the drying kinetics of seeded grapes was experimentally investigated by Cakmak and Yildiz [11]. The dryer consists of a drying chamber, a solar air collector and another collector with a PCM. The design uses swirl elements in both the entrance and the inner part of the drying chamber to obtain a swirl effect in the air flow. The proposed solar collector which was used to heat the air was manufactured with dimensions of 0.94 m × 1.85 m × 0.2 m. In addition, the absorbent surface was constructed to improve the heat transfer between the absorber plate and the flowing air. Holes with a diameter of 15 mm were drilled into the expanded-surface collector which would ensure a turbulence effect. Due to the necessity of drying the grapes within a certain drying time, another collector which included a PCM was implemented in the design in order to perform the drying process even after sunset. Calcium chloride hexahydrate as a PCM was placed at the lower section of this collector. The dimensions of the storage collector were 0.93 m × 1.93 m × 0.2 m. To improve the falling of sun rays on the collector surface, mirrors were mounted on the tripod edges of the collector which had the PCM. Simply, after sunset, the air was forced to pass through the PCM surface by a fan. Hence, the air temperature was increased due to the stored solar energy. This ensures the benefit of the continuous drying process even after sunset. The authors conducted their experiment by using three different air velocities. Their study indicated the inverse relation between the air velocity increment and the drying time period. Moreover, moisture ratio curves have been compared with six different moisture ratio correlations in the literature. The comparison showed that the Midilli model gives the most appropriate results for each drying state in the seeded grape drying process. Esakkimuthu et al. [12] developed an indirect solar dryer which utilizes a PCM. The dryer consists of a solar air heater, a blower, a packed bed type PCM thermal storage unit, and a drying chamber. A double pass V-corrugated solar air collector was used. The collector was made of three panels of a total area 6 m^2. A V-corrugated aluminum sheet of 1.1 mm thickness, V-corrugation height of 38 mm and an included angle of 60° was used as the absorber plate. The height of the air duct between the absorber and the bottom surface is 15 cm. A 5 mm toughened glass was placed tightly above the absorber surface in rubber footing. Rock wool of the thickness of 25 mm and 50 mm was used to insulate the two sides and the bottom of the collector, respectively. The thermal energy storage tank (1.8 m length and 0.4 m diameter) is made of a galvanized iron sheet and insulated with glass wool which is covered with an aluminum cladding to prevent the insulation from deteriorating due to rain and wind. Spherical capsules, made of high density polyethylene, filled with a PCM (HS 58) are kept inside the storage tank. They concluded that the collector efficiency was increased when the mass flow rate increased; this increment can be related to the reduction in the heat losses associated with the decrease of the average temperature of the collector. Moreover, the increase in the value of the heat transfer coefficient at a higher mass flow rate can be considered as another factor. The selection of the PCM with a suitable phase change temperature is important and is a key factor in order to avoid the spoiling of the food products. The proposed storage tank with the selected size of the PCM balls and a mass flow rate of 200 kg/h can provide a near uniform rate of heat exchange with minimum additional energy consumption. Hence, it will overcome the pressure drop during the charging and discharging processes.

In addition, the maximum capacity of the PCM and a uniform supply of the storage system can be achieved by using lower mass flow rate [12].

To conclude, efforts of rational and effective energy management, as well as environmental considerations, increase the interest in using renewable energy sources, in particular solar energy. However, due to the discrepancy between the energy supply and demand in solar heating applications, the thermal energy storage device has to be used for the most effective utilization of such type of energy source. The concept of "solar thermal energy storage using PCM in the solar dryer" reduces the time between energy supply and energy demand, such that it plays a vital role in energy conservation and improves the solar drying energy systems by increasing the reliability for continuous drying of agricultural food products. The previous efforts dealt with normal agriculture/food products. However, drying of medical plants is proposed to be a new trend in using the phase change materials.

To improve the thermal performance of the indirect solar dryers, the thermal performance of the solar air heater connected to the drying chamber should be improved. The next section reviews the methods that were used to improve the thermal performance of the solar air heaters with a PCM as the storage medium.

3. Review of solar air heaters with PCM as energy storage medium

3.1. Solar air heaters with built-in PCM as energy storage medium

In solar air heaters with built-in PCM as the energy storage medium, the heater mainly consists of a glass cover, an absorber plate, a PCM and insulation. The PCM is usually introduced in capsules of different shapes under the absorber plate. In such systems, part of the absorbed solar energy is transferred to the flowing air and the other is stored as latent heat. A simple design of the solar air heater with built-in thermal energy storage system was proposed and analyzed by Fath [13]. The author used a corrugated set of tubes as the heater absorber. These tubes were filled with a PCM (paraffin wax). This integrated system adds no complexity to the conventional solar air heater design, operation and maintenance. The results showed that, for an air flow rate of 0.02 kg/s, the system achieves a 63.35% daily average efficiency and the hot air outlet temperature (5 °C above ambient temperature) was extended for about 16 h, as compared to 38.7% and 9 h, respectively, for the conventional flat plate solar air heater. For an air flow rate of 0.01 kg/s, the hot air outlet temperature was extended for about 21 h. This confirms the finding of Esakkimuthu et al. [12]. The thermal performance of a thermosyphon solar air heater with a built-in latent heat thermal energy storage system was also presented by Fath [14]. A staggered set of tubes filled with a PCM was used as the energy storage absorber. Phase change materials of different melting temperatures of 61, 51, 43 and 32 °C were studied. The obtained results were compared with the system without storage material. It was found that the solar air heater with PCMs of 51 and 43 °C melting temperatures gives the best thermal performance. The solar air heater can discharge the thermal load of a minimum of 0.01 kg/s air flow rate and up to 8 °C outlet to inlet air temperature difference for 24 h of the day when the PCM melting temperature is 43 °C. The daily average efficiency of the heater varies between 27% and 63.8%, depending on the PCM melting temperature, solar intensity and mass flow rate of the flowing air. Enibe [15] introduced the transient thermal analysis of a natural convection solar air heater. The solar air heater consisting of a single-glazed flat plate collector of area of 1.503 m^2 was integrated with a paraffin type PCM. The PCM, with a total mass of about 65 kg, was prepared in modules which are spaced evenly across the absorber plate. The modules were made of slender rectangular channels whose tops were welded to the absorber plate and the bottoms rested on the bottom insulation of the solar air heater. The space between each module pair serves as an air heating duct, with the ducts being connected to common air inlet and discharge header manifolds. The predicted results of the solar air heater compare well with the experiment within the limits of experimental error. The predicted results showed that the day-long maximum predicted cumulative useful and overall efficiencies are 13% and 18%, respectively. Alkilani et al. [16] predicted the outlet air temperature due to the discharge process in a solar air heater integrated with a PCM unit, for eight different values of mass flow rates. This design consists of a single-glazed solar air heater. The heater is integrated with a PCM unit which is in turn divided into cylinders as an absorber-container installed in the collector in a cross flow of air. In order to obtain the optimum flow rate, outlet air temperature and the freezing time of the PCM, eight different mass flow rates starting from 0.05 to 0.19 kg/s were utilized. The PCM composites of paraffin wax with 0.5% mass fraction of aluminum powder was used to enhance the conduction heat transfer process. The freezing time of the PCM has been predicted for the investigated mass flow rate. It was concluded that the freezing time of the PCM is inversely proportional to the mass flow rate; it took a longer time approximately (8 h) with a flow rate of 0.05 kg/s. Goyal et al. [17] adopted an air collector employing different thermal energy storage materials (concrete, brick, sand, ground and paraffin wax) on top, but with soil provided at the bottom. The numerical computation results showed that there was a significant phase shift (10–12 h) owing to the storage effect.

3.2. Solar air heaters connected to a heat exchanger with PCM

Low thermal conductivity is a common problem for the PCMs; many studies were performed on air flowing as a heat transfer fluid with the PCM as a storage medium encapsulated in various geometries in a separated container connected to the solar air heater. Morrison and Abdel-Khalik [18] conducted a parametric study to determine the optimum physical properties of the PCM storage materials for solar air heating systems. They used simulation techniques to determine the system performance over the entire heating season for different space heating loads. Jurinak and Abdel-Khalik study [19] adopted the simulation technique to describe the transient behavior of phase change energy storage (PCES) units. They used sodium sulfate decahydrate and paraffin wax as storage media and calculated the optimum ranges of storage sizes and the variation of the solar supplied fraction of load with storage size and collector area of the systems. Hammou and Lacroix [20] presented a hybrid thermal energy storage system (HTESS). They presented and validated a mathematical model to predict the thermal performance of the HTESS. Experimental data of a prototype of the HTESS were employed to validate the model. The proposed system's thermal performance was evaluated for two different PCMs. Their investigation indicated that the electricity consumption is reduced by 32% when using a HTESS and more than 90% of the electricity is consumed during off-peak hours. Qi et al. [21] described a solar heat pump heating system with seasonal latent heat thermal storage (SHPH–SLHTS). The SHPH–SLHTS system provided sufficient heating to a villa building. The large latent heat storage tank maintained the mean designed air temperature at 18 °C, without significant variation. In addition, they used an auxiliary heat source when an insufficient storage tank was utilized. Tyagi et al. [22] conducted an experimental study to investigate the solar air heating system with and without a thermal energy storage (TES) material for energy and exergy

analyses. They used paraffin for latent heat storage and hytherm oil for sensible heat storage. They calculated the first law and the second law efficiencies on the basis of the experimental observations for three different arrangements. These arrangements were as follows: one without heat storage material and two arrangements with THES, viz. hytherm oil and paraffin wax. They related the fluctuation in both efficiencies to solar radiation fluctuations during the day. It the beginning as time increases, both efficiencies increased, and then decreased in the case without the temporary storage material. This trend was found for solar radiation as well. In the second case, without THES material, the efficiency increased with time, and attained its peak in the first half and then decreased afterward. However, in the third case, temporary heat storage material, both efficiencies increased with time. The peaks occurred at approximately 16:30 h and were accompanied by a small fluctuation with flow rate, and then decreased smoothly. Performance analysis of a latent heat storage system with a PCM for newly designed solar collectors in greenhouse heating was introduced by Benli and Durmus [23]. They investigated five designs (corrugated, reverse corrugated, trapeze, reverse trapeze, and flat) of solar air collectors. They used $CaCl_2 \cdot 6H_2O$ as the PCM with a melting temperature of 29 °C. They concluded that the proposed solar air collectors and the selected PCM system created a 6–9 °C temperature difference between the inside and the outside the greenhouse. Saman et al. [24] studied the thermal performance of a phase change thermal storage unit based on a solar roof integrated heating system. The storage unit consists of several layers of PCM slabs with a melting temperature of 29 °C. Warm air was circulated in a roof integrated collector which passed through the spaces between the PCM layers in order to charge the storage unit. The stored energy was utilized to heat the ambient air before entering a living space. They reported the following conclusions:

(1) The effect of sensible heat was observed in the initial periods of both the melting and the freezing processes. This was reflected as a sharp increase in the outlet air temperature in the initial periods for both melting and freezing.
(2) The heat transfer rates increased and the melting time shortened with high inlet air temperature. On the other hand, during the freezing process lower inlet air temperature increased the heat transfer rates and shortened the freezing time.
(3) The higher the air flow rate, the more the heat transfer. Consequently, the melting time was decreased and the outlet air temperature was increased. For the freezing process, a higher air flow rate increased the heat transfer rate, while the freezing time period and the outlet air temperature were reduced.

From a previous literature survey, it is obvious that most of the studied solar drying systems have employed paraffin wax as a storage material due to its low cost and availability. Unfortunately, most kinds of paraffin suffer from low thermal conductivity which delays the discharging process of the storage systems. Therefore, the next sections will concern the previous methods that were used for improving the thermal conductivity of paraffin waxes.

4. Previous methods used for improving the thermal conductivity of paraffin wax

Despite the fact that paraffin wax is cheap and has moderate thermal energy storage density, its main drawback is the poor thermal conductivity. One of the effective ways of increasing paraffin wax thermal conductivity is to add some material of high thermal conductivity such as carbon fibers, graphite and metal foams that will be discussed as follows.

4.1. Carbon fibers

Fukai et al. [25] used carbon fibers as a high thermal conductivity material. They investigated two different enhancement techniques. The first technique uses oriented fibers randomly, while the other is using a fiber brush. The carbon fibers essentially enhance the effective thermal conductivity of fibers/paraffin composites. The authors concluded that the random type and the fibers' length have little effect on the effective thermal conductivity of the PCM. However, the fiber brush increases the effective thermal conductivities to the maximum expected values. Moreover, the fiber brush is also useful for enhancing the effective thermal conductivities of packed beds of particles. Recently, Fukai et al. [26] used carbon fiber brushes by inserting them on the shell side of a heat exchanger to enhance conductive heat transfer rates. The experimental results showed that the brushes essentially improve the heat exchange rate during the charge and discharge processes even when the volume fractions of the fibers are about one percent.

Elgafy et al. [27] studied the effect of adding carbon nanofibers to the paraffin wax's thermal performance experimentally and analytically. The transient temperature response of the nanocomposite was measured during its solidification process and the cooling rate was predicted. They found that nanocomposite thermal conductivities were enhanced significantly causing the cooling rate to increase. An analytical model was introduced based on a one-dimensional heat conduction approach to predict the effective thermal conductivity for the new nanocomposites and it was in a good agreement with the experimental data. Yu et al. [28] used varies types of nanofibers. These types include pristine and carboxyl-functionalized short multi-walled carbon nanotubes (MWCNTs), long MWCNTs, carbon nanofibers, and graphene nanoplatelets (GNPs). The thermal conductivity of the suspensions was measured using the transient hot-wire method at a constant temperature. Experimental measurements reveal that the GNPs, owing to their particular two-dimensional planar structure, have a much greater potential in thermal conductivity increase than that of the other wire-shaped carbon nanomaterials.

Zhang et al. [29] developed a carbon nanofiber, conductive filler composite. They experimentally investigated the energy release performance of the CNF/paraffin wax composite. Their findings indicated that the thermal storage increased to five times that of a traditional thermal storage medium such as ceramic bricks (54 kJ/kg). This has been confirmed by Wang et al. [30] as the thermal conductivity enhancement ratios reach 35% in solid state and 40% in liquid state. Moreover, Sanusi et al. [31] embedded the graphite nanofiber (GNF) PCM between two sets of aluminum fins. The results indicated a notable shortening of the solidification time by 61% over the pure paraffin.

Ehid et al. [32] overcame the settling of the graphite nanofibers which occurs in the first heating–cooling cycle by creating a shape stabilized PCM using high density polyethylene (HDPE) as a stabilizing polymer. This technique eliminated GNF settling over repeated thermal cycles with as little as 10% HDPE by weight.

4.2. Expanded graphite

Expanded graphite (EG) has been intensively used during the past few years to improve paraffin thermal conductivity. There were several successful attempts to use EG to improve the thermal conductivity of paraffin; among these are Zhao et al. [33], Zhong et al. [34] and Sari and Karaipekli [35]. Xia et al. [36] prepared an EG/paraffin composite, with the mass fraction of EG varying from

0 to 10 wt%. Compact EG networks were formed gradually with an increase in the mass fraction of EG. This technique improved the thermal conduction of the composite. The authors indicated that an addition of 10 wt% EG resulting in a more than 10-fold increase in the thermal conductivity accompanied a shift in the phase change temperature. Similarly, Zhang et al. [37] prepared paraffin/EG of 92/8 wt%. The melting temperature and latent heat of the composite were found to be 52.2 °C and 170.3 J/g, respectively.

A composite based on paraffin, styrene–butadiene–styrene (SBS) triblock copolymer and exfoliated graphite was prepared by Xiao et al. [38]. In this composite, the paraffin undergoes a solid–liquid phase change in the SBS network, and there is no leakage of it even in the state of melting. The composite exhibits high thermal conductivity and nearly 80% of the latent heat of fusion per unit mass of the paraffin. Nano-graphite (NG) paraffin composites were prepared and the microstructure and thermal properties of the materials were examined by Li [39]. The results indicated that the NG layers were randomly dispersed in the paraffin, and the thermal conductivity increased gradually with the content of NG. The thermal conductivity of the material containing 10% NG was found to be 0.9362 W/m K. The cellular graphite/paraffin composites which were prepared by Vitorino et al. [40] show remarkable enhancement of thermal conductivity, in the range of 5–8 W/m K. Two paraffin composites filled separately with randomly distributed graphite nanosheets (R-GNs) and oriented graphite nanosheets (O-GNs) were fabricated, and their thermal properties and structural characteristics were investigated by Chen et al. [41]. The experimental results showed that a conductive network at 1.0 wt% graphite nanosheet (GN) loading was found. The thermal conductivities of the R-GNs/paraffin and the O-GNs/paraffin composites are 4.47 ± 0.15 and 1.68 ± 0.07 W/m K, respectively, when 5.0 wt% GNs were introduced. The Maxwell–Euken model and the modified rule of mixtures model were proposed to predict the thermal conductivities of the R-GNs/paraffin and the O-GNs/paraffin composites, respectively. The melting point and the solid–liquid phase transition temperature of the R-GNs/paraffin composites are approximately 53 and 60 °C, respectively, and neither of these values was significantly affected by the presence of GNs. Decreases in the latent heat of the R-GNs/paraffin composites with increased GN loading were also found.

Zhang et al. [42] introduced a different type of PCM composite by impregnating paraffin (P) into halloysite nanotube (HNT). Then they enhanced the P/HNT thermal storage composite by adding graphite. They concluded that the melting temperature and latent heat of composite (P/HNT: 65/35 wt%) were found to be 57.16 °C and 106.54 J/g, respectively. In addition, the graphite reduces the melting and freezing times by 60.78% and 71.52%, respectively, compared with the composite without graphite. Zhang et al. [43] studied the effect of adding EG to a high-density polyethylene (HDPE)/paraffin composite and compared the result when EG was replaced with an intumescent flame retardant (IFR) as a shape-stabilizer. They concluded that the improvement of the thermal conductivity when adding EG is much greater than when using IFR. These findings confirmed Cai et al.'s [44] measurements which indicated the minor effect on both paraffin/high density polyethylene PCM's peak temperature and thermal conductivity when adding an ammonium polyphosphate (APP) flame retardant. However, the additives of EG improved the PCM thermal stability properties which is in agreement with Zhang et al. [43]. In order to improve the paraffin wax/EG composite there are several trails to add different materials. Li et al. [45] added silicon dioxide (SiO_2) and the results indicated that the thermal conductivities of the SiO_2/paraffin composite and the SiO_2/paraffin/EG composite are 28.2% and 94.7% higher, respectively, than that of paraffin. Similarly, Fang et al. [46] investigated the effect of SiO_2 as a fire resistant material in microencapsulated paraffin composites. The study referred to the improvement in the thermal stability of the microencapsulated paraffin composites due to the synergistic effect between the paraffin and SiO_2.

4.3. Graphite foams

Zhong et al. [47] implemented mesophase pitch based graphite foams (GFs) to increase the thermal diffusivity of paraffin wax. The thermal diffusivity of the Paraffin-GF can be enhanced 190, 270, 500, and 570 times as compared with that of pure paraffin wax. The key factors of such improvement are pore-size and thickness of ligaments of the foam. Small pore-size and thicker ligament in the GF improves the composite thermal diffusivity, While, large pore-size and thinner ligament increases the composite latent heat. Chintakrind et al. [48] used graphite foam with infiltrated PCM, aluminum foam with infiltrated PCM, and PCM with 10 wt% graphite nanofibers (GNF). The results indicated that the aluminum and graphite foams were more effective at base temperature control than the GNF/PCM mixture and base paraffin, respectively. Although the foams improved the heat sink ability, they have low effect in the FCM steady state period. A paraffin/copper foam (metal foam, a metallic porous matrix material, is a porous medium that exhibits the excellent combination of compactness, low weight, and high thermal conductivity) composite was investigated by Cui [49] and Li et al. [50]. Paraffin/copper nanofluid composites were studied experimentally by Wu et al. [51]. The experimental results indicate that the copper foam enhanced the heat transfer rate and improved the thermal conductivities of the paraffin composites. Mills et al. [52] experimentally studied the thermal conductivity improvement when using a graphite matrix. The results showed that the composite matrix has a thermal conductivity that is 20–130 times greater than the thermal conductivity of the pure paraffin.

4.4. High thermal conductive particles

Paksoy and Sahan [53] prepared paraffin/nano-magnetite (Fe_2O_3) nanocomposites. The results showed that the nano-magnetite is homogeneously distributed in the paraffin structure and the thermal storage capacity of the paraffin can be increased by about 20% by adding 10% of nano-magnetite. Arasu and Mujumdar [54] used Al_2O_3 and their experimental investigation concluded that the latent heat storage capacity of paraffin wax can be significantly increased by adding a smaller volumetric concentration of alumina particles in the paraffin wax. Similarly, Ho and Gao [55] embedded emulsifying alumina (Al_2O_3) nanoparticles in paraffin (n-octadecane) by means of a non-ionic surfactant. They experimentally investigated the composite latent heat of fusion, density, dynamic viscosity, and thermal conductivity. They found a temperature related nonlinear increase of both thermal conductivity and dynamic viscosity. In addition, Xiang and Drzal [56] used exfoliated graphite nanoplatelets (xGnP) and Li et al. [57] used paraffin/bentonite while Ettouney et al. [58] used paraffin wax/metal beads of stainless steel.

5. Enhancement heat transfer rate inside paraffin waxes

In additions, various heat transfer enhancement techniques for paraffin as a PCM thermal storage medium were studied, such as those using fins [59,60], pin fins [61] and lessing rings [60]. Tay et al. [62] conducted an experiment to validate a computational fluid dynamics (CFD) model for tubes coiled in a phase change thermal energy storage system. They validated three different CFD models. The first model had pins embedded on a tube with a heat transfer fluid (HTF) flowing in it. However, the PCM was surrounding the tube. Different configurations of pins were analyzed. In the

second model fins were embedded instead of pins. Different configurations of fins on the tube were also investigated. The third one had a plain copper tube surrounded by the PCM with HTF flowing in it. The last model was used as a benchmark for comparisons of the first two models. They concluded that a finned tube design provides higher heat transfer rates than a pinned tube without impacting the overall energy density of the storage system. In addition, using the fins is a more effective heat transfer enhancement technique for all shell and tube and tube-in-tank type PCM thermal storage systems.

6. Conclusions and recommendations for future work

This paper reviews the previous work on solar dryers with the phase change materials (PCM) as the energy storage media. From this study, it is concluded that the recent research focused on PCMs as energy storage media because of the higher thermal energy storage density of these materials compared with sensible heat storage materials. For a better thermal performance of solar dryers a phase change material with high latent heat and with a large surface area for heat transfer is required. Using PCMs with solar dryers leads to a reduction of the heat loss and the mismatch between supply and demand and improvement of the energy efficiency of the system. The low thermal conductivity represents a common problem to most of the PCMs. Therefore, studies to investigate and improve the heat transfer between the heat transfer fluid and the PCM are still of considerable interest. Drying of medical plants is proposed to be a new trend in using phase change materials, where it needs moderate and constant temperature during the drying process. It is also proposed to use commercial numerical packages, Fluent-Ansys, to improve the dryer design which utilizes the PCM. The second objective of this review paper was to review the published papers concerned with the methods that were used to improve the thermal conductivity of paraffin waxes to be used as storage media in most moderate temperature solar energy applications. It is found that carbon fibers, expanded graphite, graphite foam and high thermal conductive particles improve the thermal conductivity of paraffin waxes significantly; therefore, they could be integrated within solar energy devices to improve their charging/discharging capabilities.

References

[1] Tchinda R. A review of the mathematical models for predicting solar air heaters systems. Renew Sustain Energy Rev 2009;13:1734–59.
[2] Bal LM, Satya S, Naik SN. Solar dryer with thermal energy storage systems for drying agricultural food products: a review. Renew Sustain Energy Rev 2010;14:2298–314.
[3] El-Sebaii AA, Aboul-Eneein S, Ramadan MRI, EL-Bialy E. Year round performance of double pass solar air heater with packed bed. Energy Convers Manag 2007;48:990–1003.
[4] El-Sebaii AA, Aboul-Enein S, Ramadan MRI, El-Gohary HG. Experimental investigation of an indirect type natural convection solar dryer. Energy Convers Manag 2002;43:2251–66.
[5] Dutil Y, Rousse DR, Salah NB, Lassue SP, Zalewski L. A review on phase-change materials: mathematical modeling and simulations. Renew Sustain Energy Rev 2011;15:112–30.
[6] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renew Sustain Energy Rev 2009;13:318–45.
[7] Bal LM, Satya S, Naik SN, Meda V. Review of solar dryers with latent heat storage systems for agricultural products. Renew Sustain Energy Rev 2011;15:876–80.
[8] Devahastin S, Ng KW, Mujumdar AS. Preliminary study of a novel thermal storage-spouted bed contactor for particulate drying. In: Proceedings of the 48th Canadian chemical engineering conference; 1989.
[9] Devahastin S, Pitaksuriyarat S. Use of latent heat storage to conserve energy during drying and its effect on drying kinetics of a food product. Appl Therm Eng 2006;26:1705–13.
[10] Bal LM, Sudhakar P, Satya S, Naik SN. Solar dryer with latent heat storage systems for drying agricultural food products. In: Proceedings of the international conference on food security and environmental sustainability; 2009.
[11] Cakmak G, Yidiz C. The drying kinetics of seeded grape in solar dryer with PCM-based solar integrated collector. Food Bioprod Process 2011;89:103–8.
[12] Esakkimuthu S, Hassabou A, Palaniappan C, Spinnler M, Blumenberg J, Velraj R. Experimental investigation on phase change material based thermal storage system for solar air heating applications. Sol Energy 2013;88:144–53.
[13] Fath HES. Thermal performance of simple design solar air heater with built in thermal energy storage system. Energy Convers Manag 1995;36:989–97.
[14] Fath HES. Transient analysis of thermosyphon solar air heater with built in latent heat thermal energy storage system. Renew Energy 1995;6(2):119–24.
[15] Enibe SO. Thermal analysis of a natural circulation solar air heating system with phase change material energy storage. Renew Energy 2003;28:2269–99.
[16] Alkilani MM, Sopian K, Mat S, Alghoul MA. Output air temperature prediction in a solar air heater integrated with phase change material. Eur J Sci Res 2009;27(3):334–434.
[17] Goyal RK, Tiwari GN, Garg HP. Effect of thermal storage on the performance of an air collector: a periodic analysis. Energy Convers Manag 1998;39:193–202.
[18] Morrison DJ, Abdel-khalil SI. Effects of phase-change energy storage on the performance of air-based and liquid-based solar heating systems. Sol Energy 1978;20:57–67.
[19] Jurinak JJ, Abdel-khalik SI. Properties optimization for phase-change energy storage in air-based solar heating systems. Sol Energy 1978;21:377–83.
[20] Hammou ZA, Lacroix M. A new PCM storage system for managing simultaneously solar and electric energy. Energy Build 2006;38:258–65.
[21] Qi Q, Deng S, Jiang Y. A simulation study on a solar heat pump heating system with seasonal latent heat storage. Sol Energy 2008;82:669–75.
[22] Tyagi VV, Pandey AK, Giridhar G, Bandyopadhyay B, Park SR, Tyagi SK. Comparative study based on exergy analysis of solar air heater collector using thermal energy storage. Int J Energy Res 2011;2:1–13.
[23] Benli H, Durmus A. Performance analysis of a latent heat storage system with phase change material for new designed solar collectors in greenhouse heating. Sol Energy 2009;83:2109–19.
[24] Saman W, Bruno F, Halawa E. Thermal performance of PCM thermal storage unit for a roof integrated solar heating system. Sol Energy 2005;78:341–9.
[25] Fukai J, Kanou M, Kodama Y, Miyatake O. Thermal conductivity enhancement of energy storage media using carbon fibers. Energy Convers Manag 2000;41:1543–56.
[26] Fukai J, Hamada Y, Morozumi Y, Miyatake O. Improvement of thermal characteristics of latent heat thermal energy storage units using carbon-fiber brushes: experiments and modeling. Int J Heat Mass Transf 2013;46:4513–25.
[27] Elgafy A, Lafdi K. Effect of carbon nanofiber additives on thermal behavior of phase change materials. Carbon 2005;43:3067–74.
[28] Yu ZT, Fang X, Fan LW, Wang X, Xiao YQ, Zeng Y, et al. Increased thermal conductivity of liquid paraffin-based suspensions in the presence of carbon nano-additives of various sizes and shapes. Carbon 2013;53:277–85.
[29] Zhang K, Han B, Yu X. Electrically conductive carbon nanofiber/paraffin wax composites for electric thermal storage. Energy Convers Manag 2012;64:62–7.
[30] Wang J, Xie H, Xin Z. Thermal properties of paraffin based composites containing multi-walled carbon nanotubes. Thermochim Acta 2009;488:39–42.
[31] Sanusi O, Warzoha R, Fleischer AS. Energy storage and solidification of paraffin phase change material embedded with graphite nanofibers. Int J Heat Mass Transf 2011;54:4429–36.
[32] Ehid R, Weinstein RD, Fleischer AS. The shape stabilization of paraffin phase change material to reduce graphite nanofiber settling during the phase change process. Energy Convers Manag 2012;57:60–7.
[33] Zhao J, Guo Y, Feng F, Tong Q, Qv W, Wang H. Microstructure and thermal properties of a paraffin/expanded graphite phase-change composite for thermal storage. Renew Energy 2011;36:1339–42.
[34] Zhong Y, Li S, Wei X, Liu Z, Guo Q, Shi J, Liu L. Heat transfer enhancement of paraffin wax using compressed expanded natural graphite for thermal energy storage. Carbon 2010;48:300–4.
[35] Sari A, Karaipekli A. Thermal conductivity and latent heat thermal energy storage characteristics of paraffin/expanded graphite composite as phase change material. Appl Therm Eng 2007;27:1271–7.
[36] Xia L, Zhang P, Wang RZ. Preparation and thermal characterization of expanded graphite/paraffin composite phase change material. Carbon 2010;48:2538–48.
[37] Zhang Z, Zhang N, Peng J, Fang X, Gao X, Fang Y. Preparation and thermal energy storage properties of paraffin/expanded graphite composite phase change material. Appl Energy 2012;91:426–31.
[38] Xiao M, Feng B, Gong K. Thermal performance of a high conductive shape-stabilized thermal storage material. Sol Energy Mater Sol Cells 2001;69:293–6.
[39] Li M. A nano-graphite/paraffin phase change material with high thermal conductivity. Appl Energy 2013;106:25–30.
[40] Vitorino N, Abrantes JCC, Frade JR. Cellular PCM/graphite composites with improved thermal and electrical response. Mater Lett 2013;92:100–3.
[41] Chen YJ, Nguyen DD, Shen MY, Yip MC, Tai NH. Thermal characterizations of the graphite nanosheets reinforced paraffin phase-change composites. Compos: Part A 2013;44:40–6.
[42] Zhang J, Zhang X, Wan Y, Mei D, Zhang B. Preparation and thermal energy properties of paraffin/halloysite nanotube composite as form-stable phase change material. Sol Energy 2012;86:1142–8.

[43] Zhang P, Hu Y, Song L, Ni J, Xing W, Wang J. Effect of expanded graphite on properties of high-density polyethylene/paraffin composite with intumescent flame retardant as a shape-stabilized phase change material. Sol Energy Mater Sol Cells 2010;94:360–5.
[44] Cai Y, Wei Q, Huang F, Lin S, Chen F, Gao W. Thermal stability, latent heat and flame retardant properties of the thermal energy storage phase change materials based on paraffin/high density polyethylene composites. Renew Energy 2009;34:2117–23.
[45] Li M, Wu Z, Tan J. Properties of form-stable paraffin/silicon dioxide/expanded graphite phase change composites prepared by sol–gel method. Appl Energy 2012;92:456–61.
[46] Fang G, Chen Z, Li H. Synthesis and properties of microencapsulated paraffin composites with SiO_2 shell as thermal energy storage materials. Chem Eng J 2010;163:154–9.
[47] Zhong Y, Guo Q, Li S, Shi J, Liu L. Heat transfer enhancement of paraffin wax using graphite foam for thermal energy storage. Sol Energy Mater Sol Cells 2010;94:1011–4.
[48] Chintakrinda K, Weinstein RD, Fleischer AS. A direct comparison of three different material enhancement methods on the transient thermal response of paraffin phase change material exposed to high heat fluxes. Int J Therm Sci 2011;50:1639–47.
[49] Cui HT. Experimental investigation on the heat charging process by paraffin filled with high porosity copper foam. Appl Therm Eng 2012;39:26–8.
[50] Li WQ, Qu ZG, He YL, Tao WQ. Experimental and numerical studies on melting phase change heat transfer in open-cell metallic foams filled with paraffin. Appl Therm Eng 2012;37:1–9.
[51] Wu S, Wang H, Xiao S, Zhu D. Numerical simulation on thermal energy storage behavior of Cu/paraffin nanofluids PCMs. Proc Eng 2012;31:240–4.
[52] Mills A, Farid M, Selman JR, Al-Hallaj S. Thermal conductivity enhancement of phase change materials using a graphite matrix. Appl Therm Eng 2006;26:1652–1661.
[53] Paksoy H, Sahan N. Thermally enhanced paraffin for solar applications. Energy Proc 2012;30:350–2.
[54] Arasu AV, Mujumdar AS. Numerical study on melting of paraffin wax with Al_2O_3 in a square enclosure. Int Commun Heat Mass Transf 2012;39:8–16.
[55] Ho CJ, Gao JY. Preparation and thermophysical properties of nanoparticle-in-paraffin emulsion as phase change material. Int Commun Heat Mass Transf 2009;36:467–70.
[56] Xiang J, Drzal LT. Investigation of exfoliated graphite nanoplatelets (xGnP) in improving thermal conductivity of paraffin wax-based phase change material. Sol Energy Mater Sol Cells 2011;95:1811–8.
[57] Li M, Wu Z, Kao H, Tan J. Experimental investigation of preparation and thermal performances of paraffin/bentonite composite phase change material. Energy Convers Manag 2011;52:3275–81.
[58] Ettouney H, Alatiqi I, Al-Sahali M, Al-Hajirie K. Heat transfer enhancement in energy storage in spherical capsules filled with paraffin wax and metal beads. Energy Convers Manag 2006;47:211–28.
[59] Stritih U. An experimental study of enhanced heat transfer in rectangular PCM thermal storage. Int J Heat Mass Transf 2004;47:2841–7.
[60] Velraj R, Seeniraj RV, Hafner B, Faber C, Schwarzer K. Heat transfer enhancement in a latent heat storage system. Sol Energy 1999;65:171–80.
[61] Baby R, Balaji C. Thermal optimization of PCM based pin fin heat sinks: an experimental study. Appl Therm Eng 2013;54:65–77.
[62] Tay NHS, Bruno F, Belusko M. Comparison of pinned and finned tubes in a phase change thermal energy storage system using CFD. Appl Energy 2013;104:79–86.